REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
	Technical Papers	

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20020917 021

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Leilani Richardson
Unclassified	Unclassified	Unclassified	A		19b. TELEPHONE NUMBER *(include area code)* (661) 275-5015

9 items enclosed

⇒ Paper Rec'd After 30-day Deadline = (21 days until Deadline)

FILE

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 21 August 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2002-207**
Mike Fife (PRSS), "Electric Propulsion: An Introduction and Development Status" (viewgraphs only)

56792

VA Tech Grad Student Seminar **(Statement A)**
(Blacksburg, VA, 09 September 2002) **(Deadline: 09 Sept 02)**

Electric Propulsion: An Introduction and Development Status

Virginia Polytechnic Institute

9 Sept, 2002

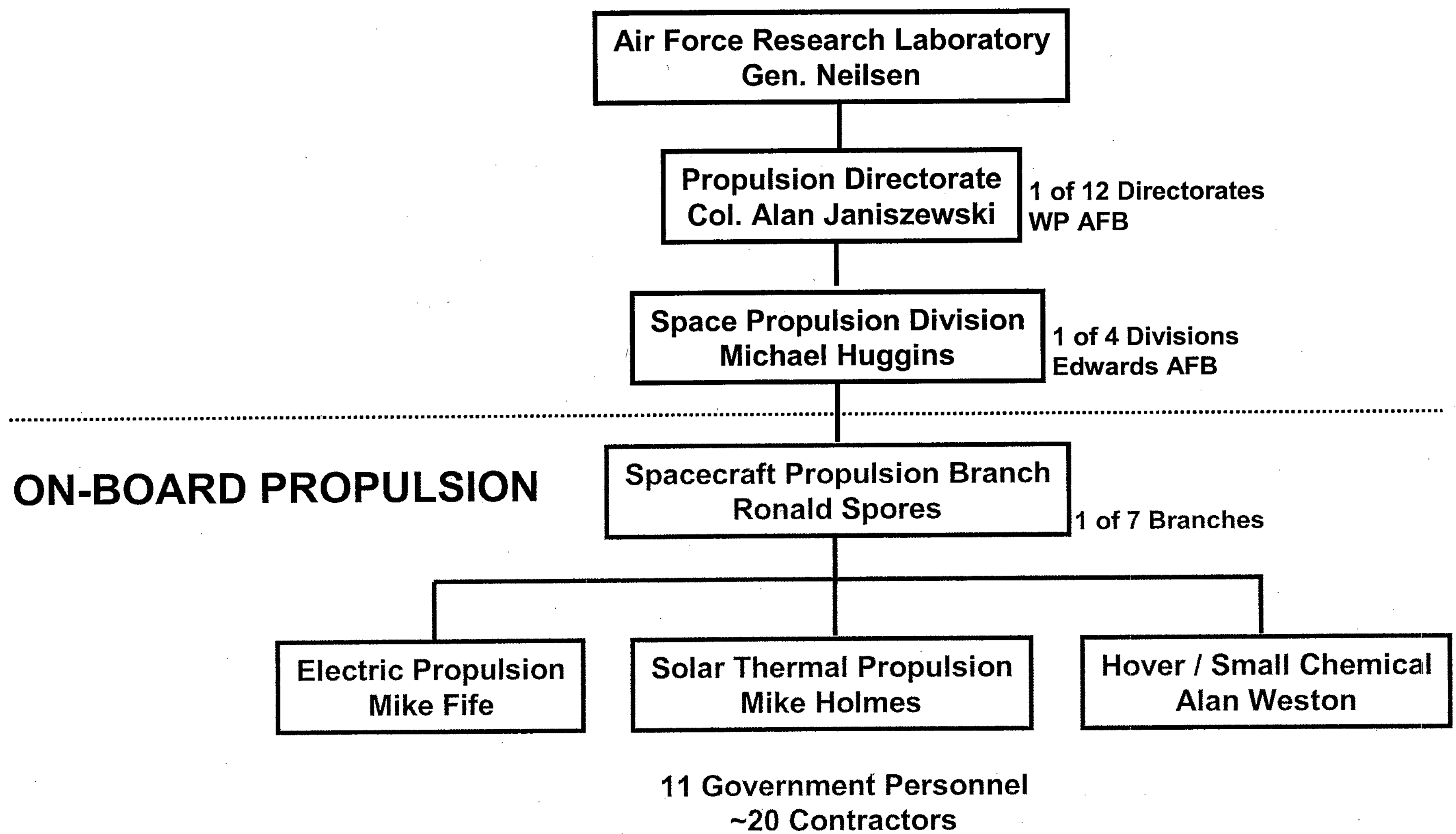
J. Michael Fife, Ph.D.
Leader, Electric Propulsion Group
Air Force Research Laboratory

Contents

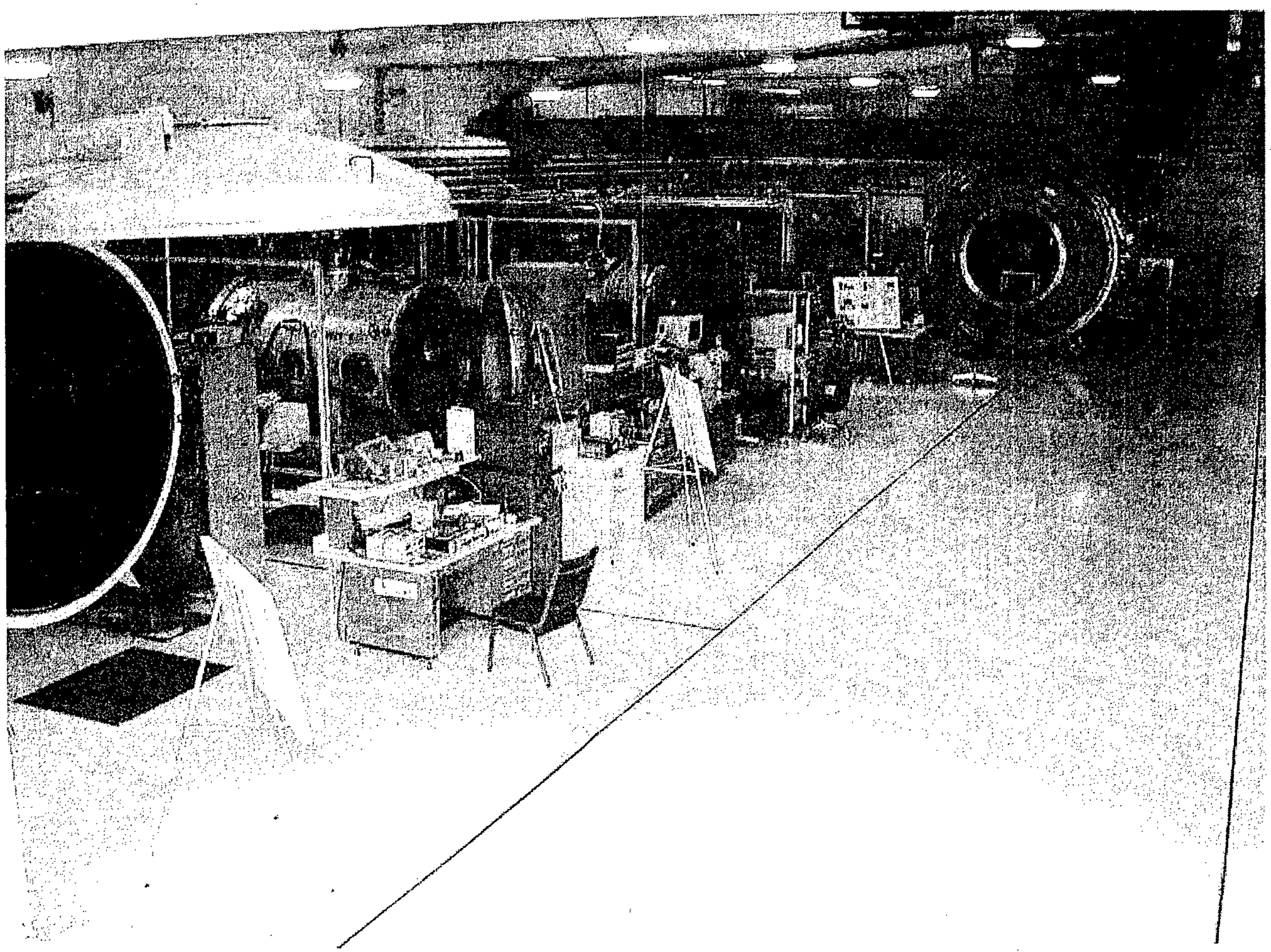
- AFRL/PRSS Laboratory Overview
- Fundamentals of Space Propulsion
- What is Electric Propulsion?
- Brief Description of Some EP Devices
- U.S. Government Hall Thruster Development
- Mission and Integration Issues
- Upcoming Air Force Missions Using EP
- Summary

AFRL EP Lab Overview

Organization



AFRL Electric Propulsion Laboratory



Edwards AFB, CA

6 Vacuum Chambers

Full Time Personnel:

- 8 PhDs
- 3 Engineers
- 3 Technicians
- 1 Financial Analyst
- 1 Admin. Assistant

Annual Budget:

~$4M

Fundamentals of Space Propulsion

Fundamentals of Space Propulsion

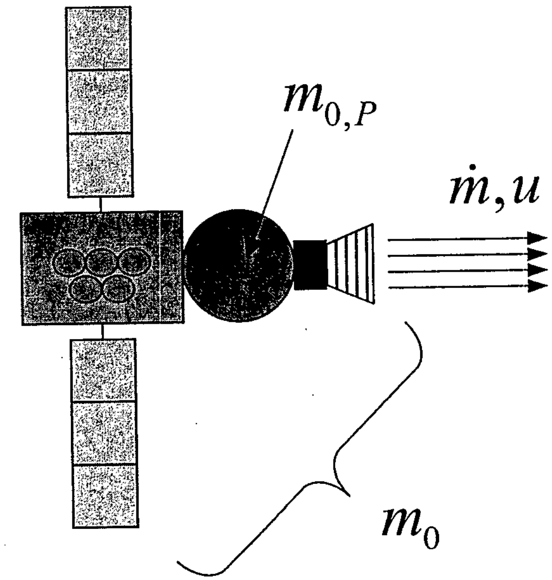
$$\left.\begin{aligned} F &= ma \\ \dot{m}u &= m\dot{v} \end{aligned}\right\}$$ **Newton's Law**

$$\frac{m_{0,P}}{m_0} = 1 - e^{\frac{-\Delta v}{u}}$$ **The Rocket Equation**

$$\left.\begin{aligned} I_{sp} = \frac{F}{\dot{m}g} = \frac{\dot{m}u}{\dot{m}g} = \frac{u}{g} \\ \boxed{I_{sp} \sim u} \end{aligned}\right\}$$ **Specific Impulse**

$$\boxed{\frac{m_{0,P}}{m_0} = 1 - e^{\frac{-\Delta v}{g I_{sp}}}}$$ **The Rocket Equation**

IMPORTANT RESULT:
For fixed fuel fraction, ΔV is proportional to I_{sp}



$F \equiv$ Thrust

$u \equiv$ Propellant Velocity

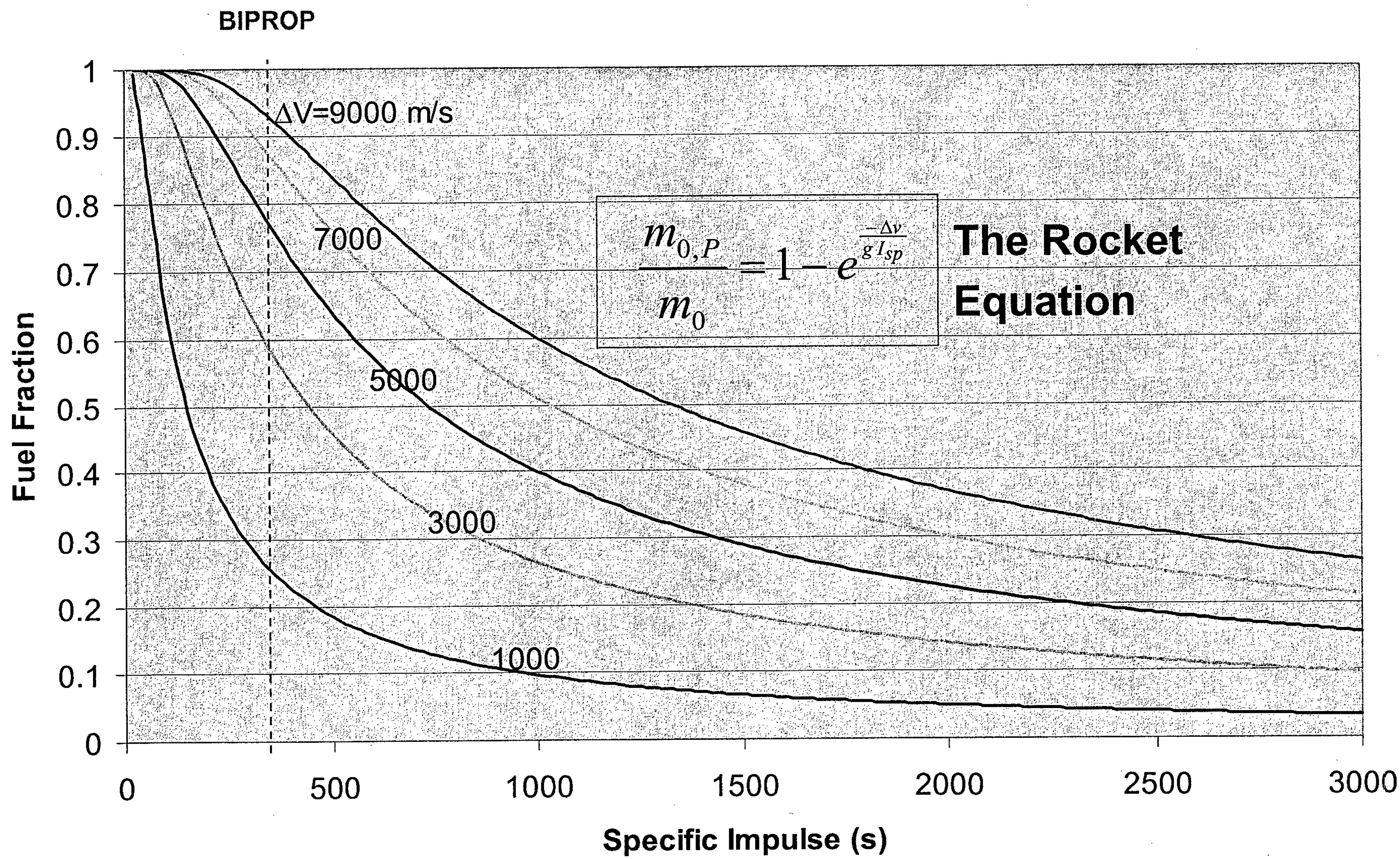
$g \equiv$ Gravitational Constant

$\dot{m} \equiv$ Propellant Flow Rate

$m_0 \equiv$ Spacecraft Mass (initial)

$m_{0,P} \equiv$ Propellant Mass (initial)

Fundamentals of Space Propulsion

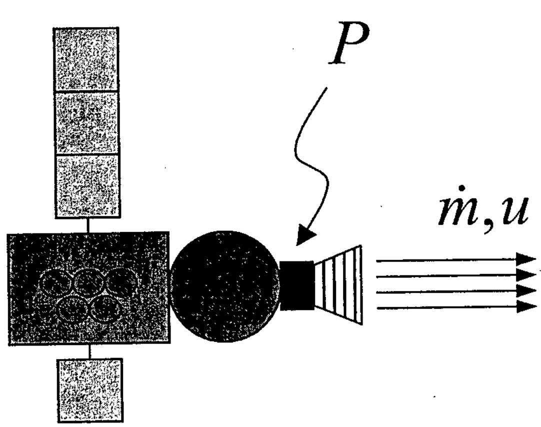


Benefits of Electric Propulsion

Chemical Propulsion

$$E_{chem} = \frac{1}{2} m u^2 \qquad u = \sqrt{\frac{2E_{chem}}{m}} \qquad \boxed{I_{sp} = \frac{u}{g} = \frac{1}{g}\sqrt{\frac{2E_{chem}}{m}}}$$

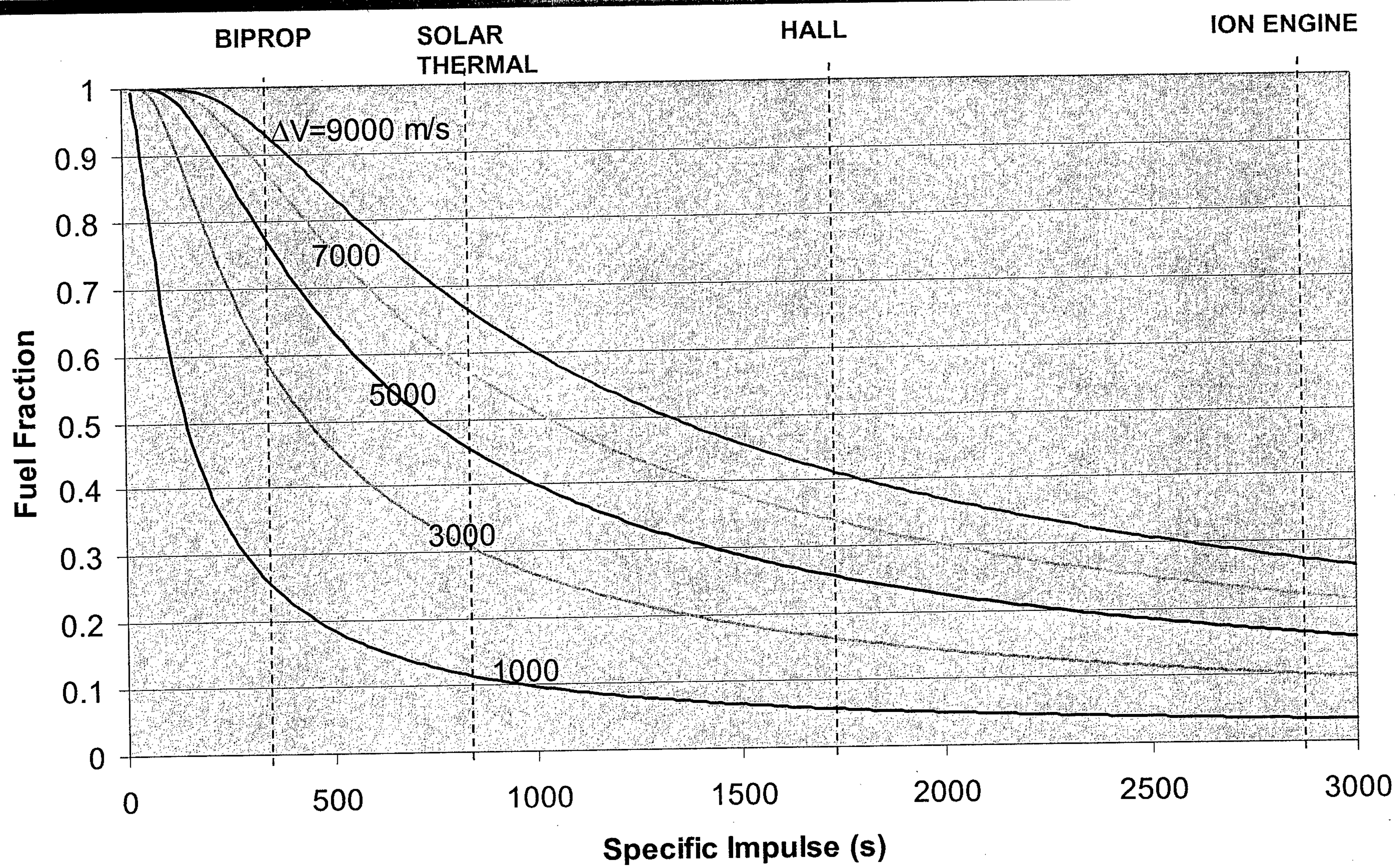
General Propulsion



$$E = \frac{1}{2} m u^2 \qquad u = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2P}{\dot{m}}}$$

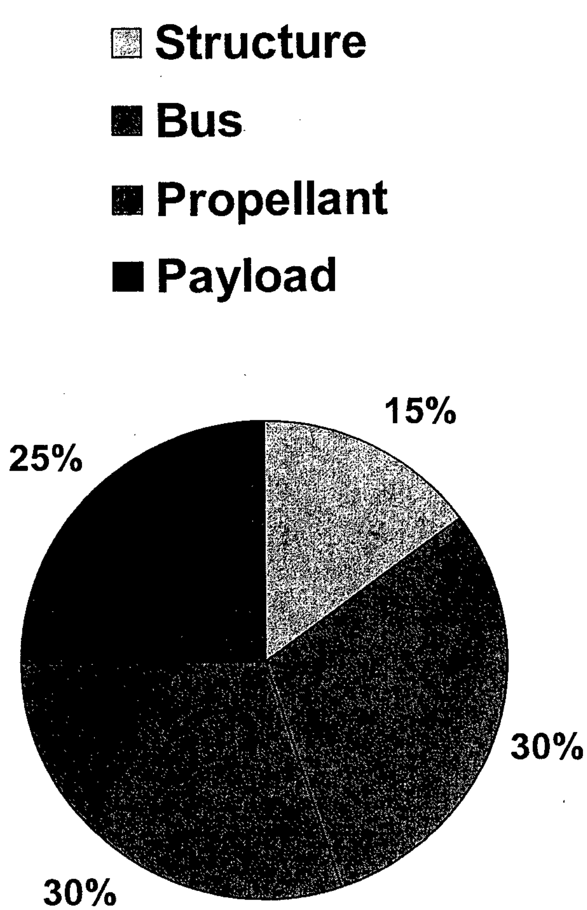
$$\boxed{I_{sp} = \frac{u}{g} = \frac{1}{g}\sqrt{\frac{2P}{\dot{m}}}}$$

Benefits of Electric Propulsion

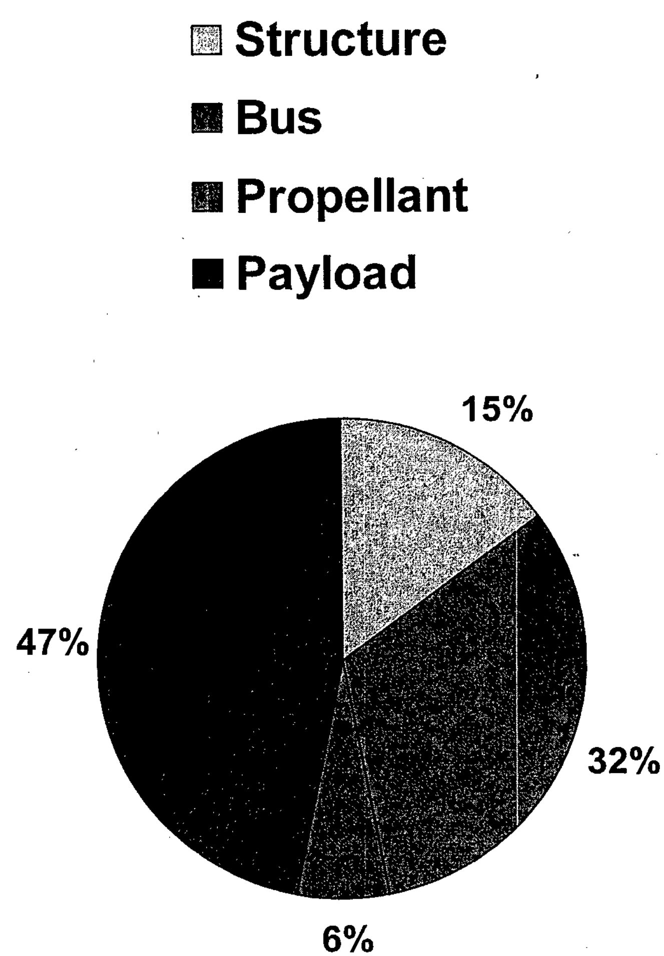


Benefits of Electric Propulsion

Chemical



Electric



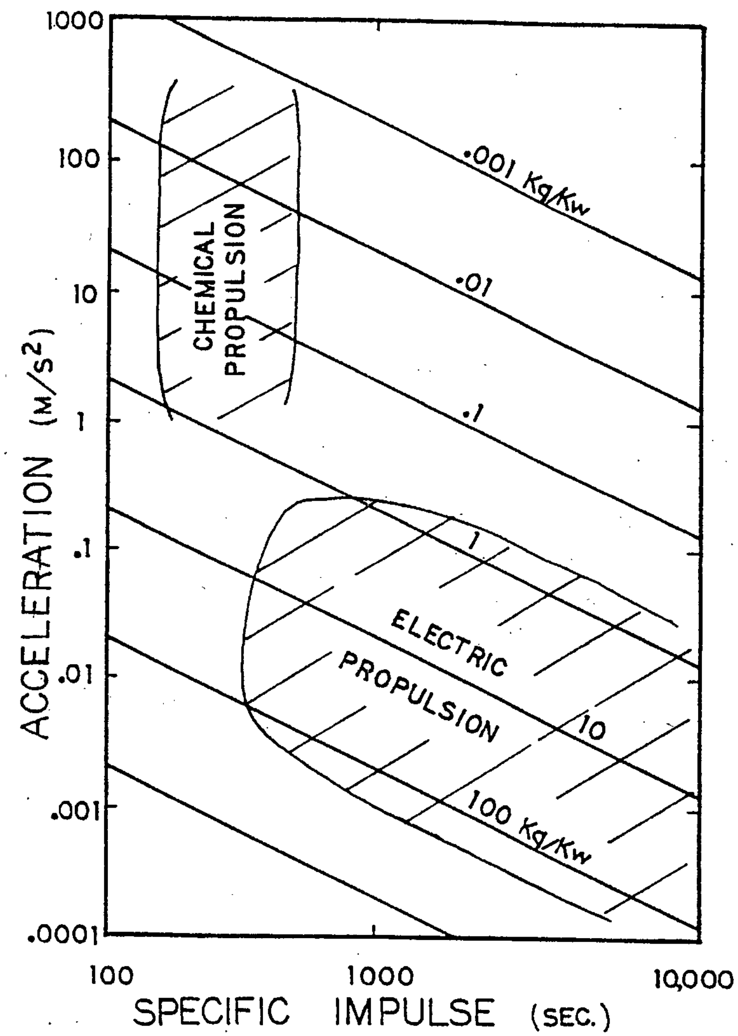
Electric Propulsion
Power Limited

JET POWER

$$P_{jet} = \frac{1}{2}\dot{m}u^2 = \frac{1}{2}(\dot{m}u)u = \frac{1}{2}FI_{sp}g$$

$$F = \frac{2P_{jet}}{I_{sp}g}$$

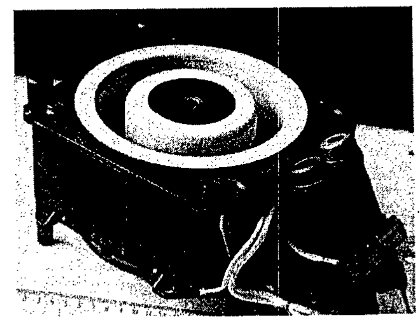
Low P_{jet}, High I_{sp} means LOW THRUST



*Prof. M. Martinez-Sanchez, M.I.T.

Electric Propulsion
Comparison with Chemical Propulsion

VS



Pratt and Whitney RL-10 **Fakel SPT-140 Hall Thruster**

Propellant	LOX/LH2	Xenon
I_{sp}	410 sec	1800 sec
P_{jet}	134 MW	4.5 kW
F	66.7 kN	300 mN

Electric Propulsion
Low-Thrust Maneuver

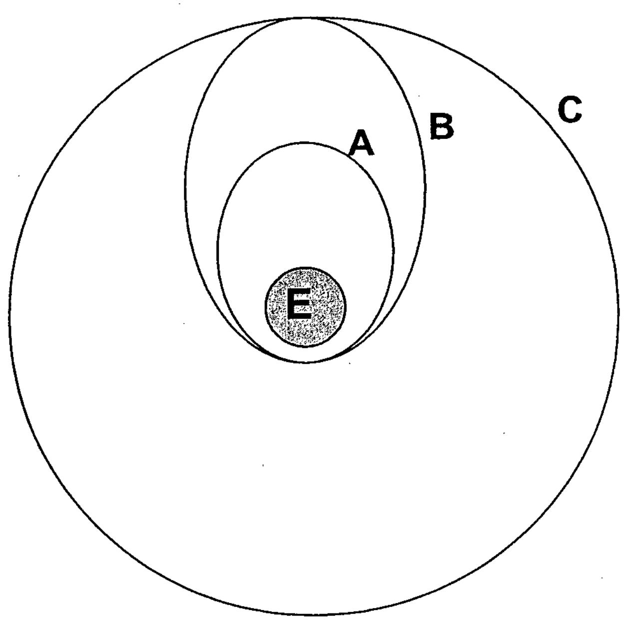
Low-thrust EP requires non-Hohmann maneuvering

<u>Example:</u> Orbit Raise of 10kW-class satellite

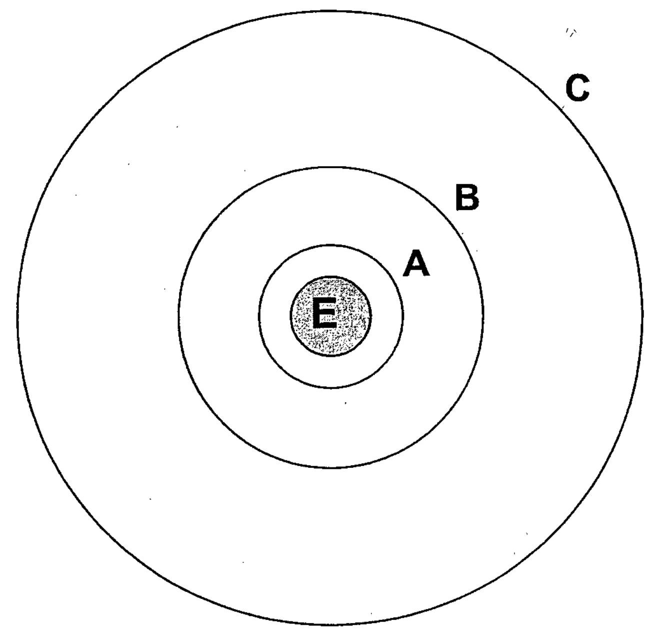
GTO-to-GEO

F=300 mN

Trip Time: ~120 days



Partial-Period Apogee Boost



Continuous Thrust Spiral

Electric Propulsion -- Review

KEY EQUATIONS

$$\frac{m_{0,P}}{m_0} = 1 - e^{\frac{-\Delta v}{g I_{sp}}}$$

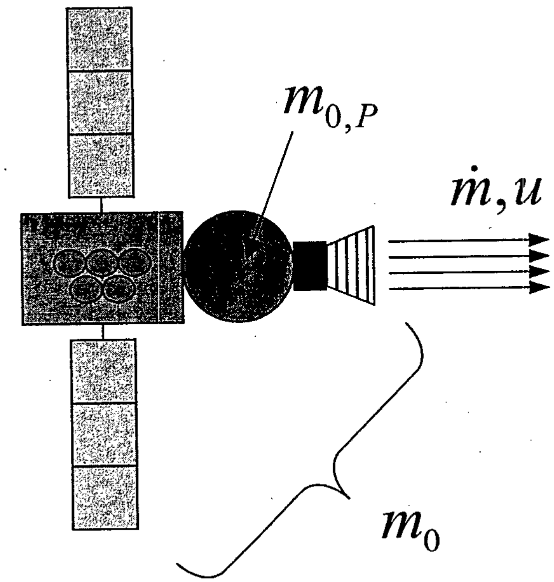
ROCKET EQUATION -- Higher I_{sp} gives higher maneuverability with less propellant

$$I_{sp} = \frac{u}{g}$$

I_{sp} is proportional to propellant exit velocity

$$F = \frac{2P_{jet}}{I_{sp} g}$$

Thrust is proportional to jet power, and inversely proportional to I_{sp}



$F \equiv$ Thrust

$u \equiv$ Propellant Velocity

$g \equiv$ Gravitational Constant

$\dot{m} \equiv$ Propellant Flow Rate

$m_0 \equiv$ Spacecraft Mass (initial)

$m_{0,P} \equiv$ Propellant Mass (initial)

- EP devices can:
  - GREATLY increase ΔV (by over 5 times)

    -or-
  - GREATLY decrease propellant fraction
- EP devices have LOW THRUST, requiring long-duration firing

A Brief Description of Some EP Devices

Typical Parameters of Small Thrusters

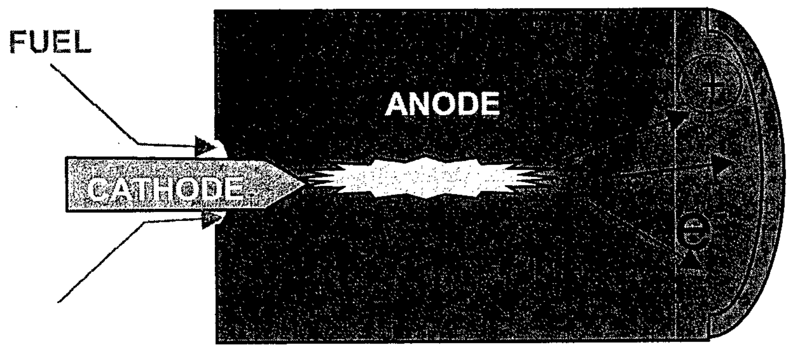
Thruster	I_{sp} (s)	η	Thrust
Solid Rocket Motor	185	90+%	100+ N
Chemical Bipropellant	315	95+%	>2 N
Arcjets	~500 - 700s >1000 s (H_2)	~30%	0.1-1 N
Pulsed Plasma Thruster	200-1500	~15%	2 μN – 4.5 mN
Colloid Thruster	450-1350	~50%	20 μN
Hall Thruster	1500-3000	~50-60%	1.8–500 mN
Ion Thrusters	1700-3900 s	~65%	1-100 mN
Field Emission Thruster	6000-9000 s	~90%	40 μN – 1.4 mN

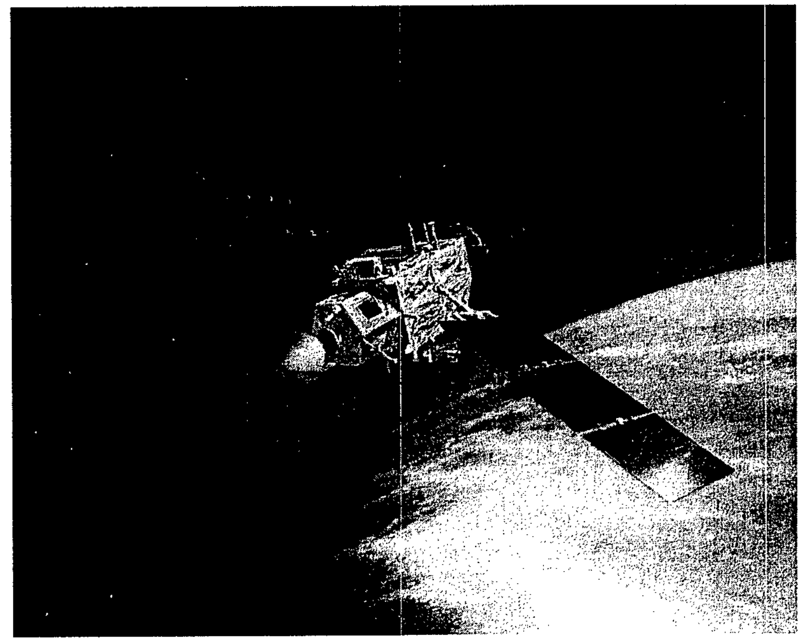
Electric Propulsion Thrusters

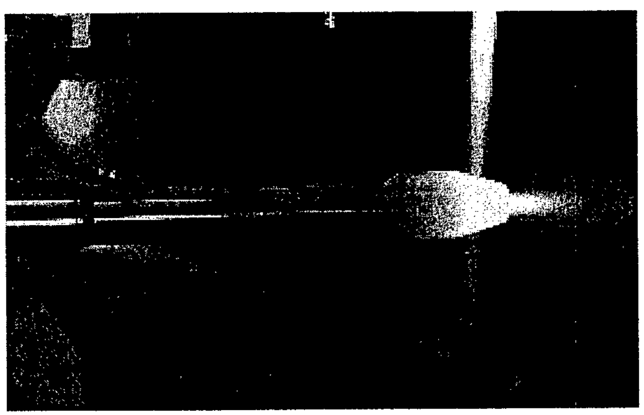
blue = used as primary maneuvering engine

Electrothermal Arcjets

- Principle: High translational energies through efficient heating
- Propellant: N_2/H_2, N_2H_4, H_2





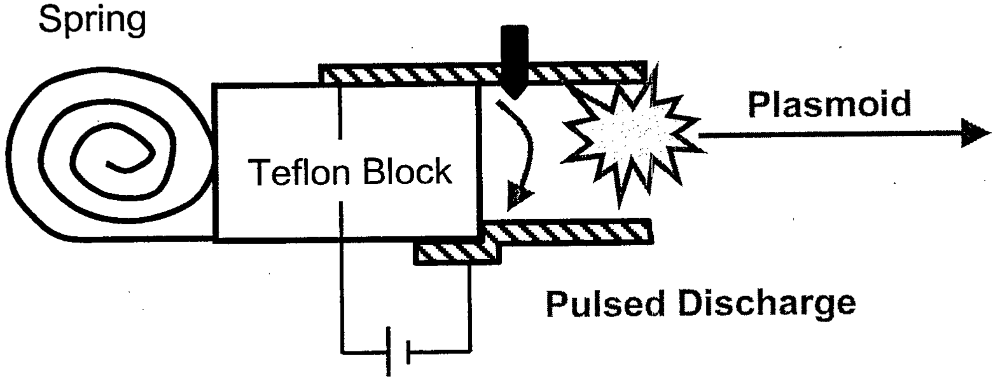


ESEX 30kW ammonia arcjet
Air Force flight experiment
Flew successfully in 1999

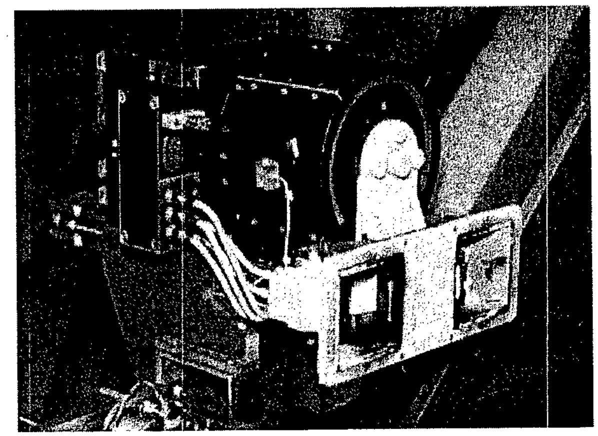
Isp = 500-1200 sec
η = 20-30%
Thrust = 0.1-1 N

Pulsed Plasma Thruster (PPT)

- Principle: Plasma Surface Ablation + Acceleration
- Propellant: Teflon, Teflon derivatives



Isp = 200 -1500 sec
η = ~15%
Thrust = 2 uN - 4 mN



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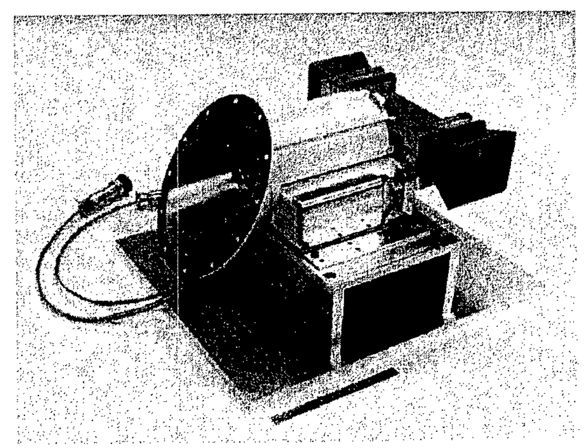
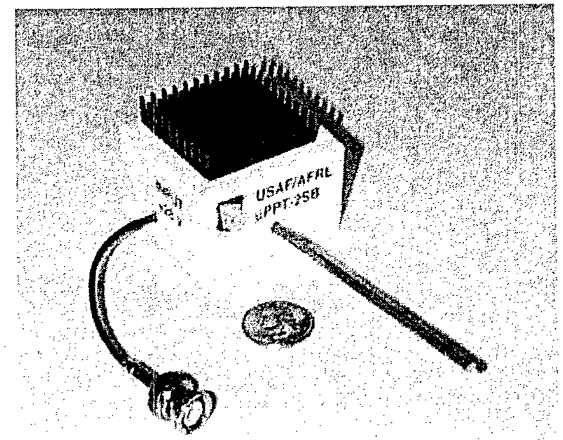


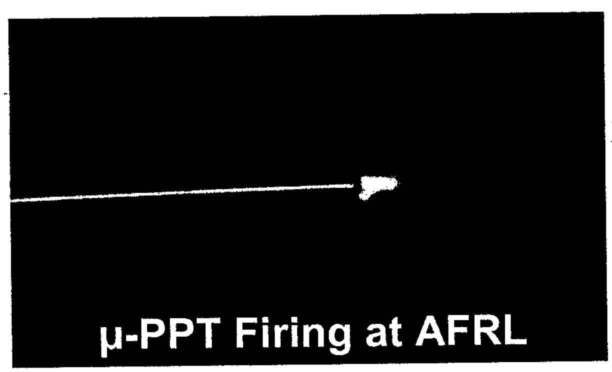
Primex EO-1

Micro-PPTs

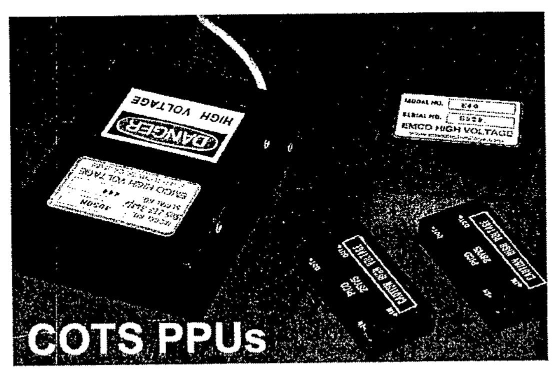
- Key development issues:
  - Thruster life as propellant recedes
  - Minimize operational voltage
  - Low mass power supplies and switching mechanisms
  - Quantify effluents
- Flight demo on TechSat 21



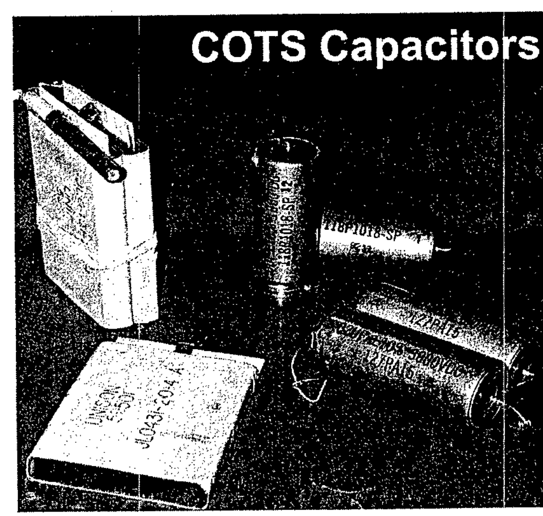
AFRL Patented Designs



μ-PPT Firing at AFRL



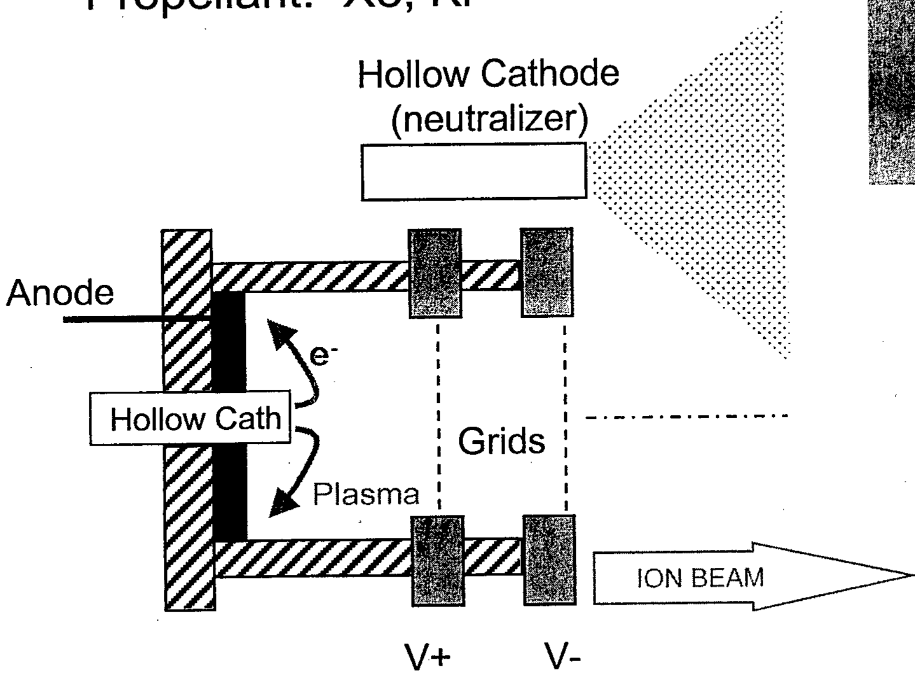
COTS PPUs

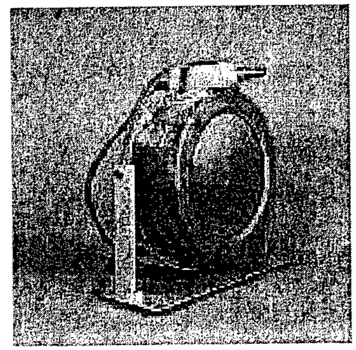


COTS Capacitors

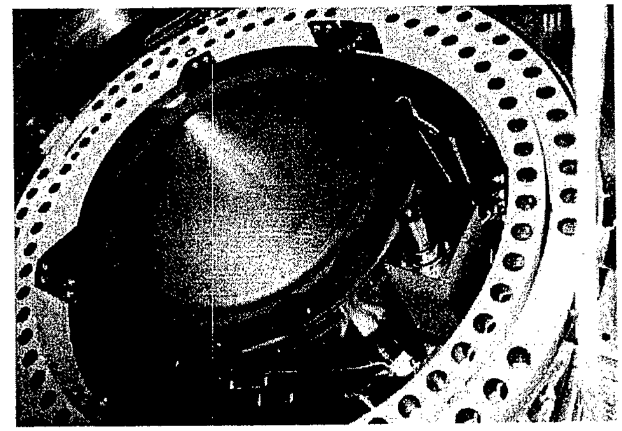
Ion Engines

- Principle:
  Electrostatic Acceleration of Ions
- Propellant: Xe, Kr

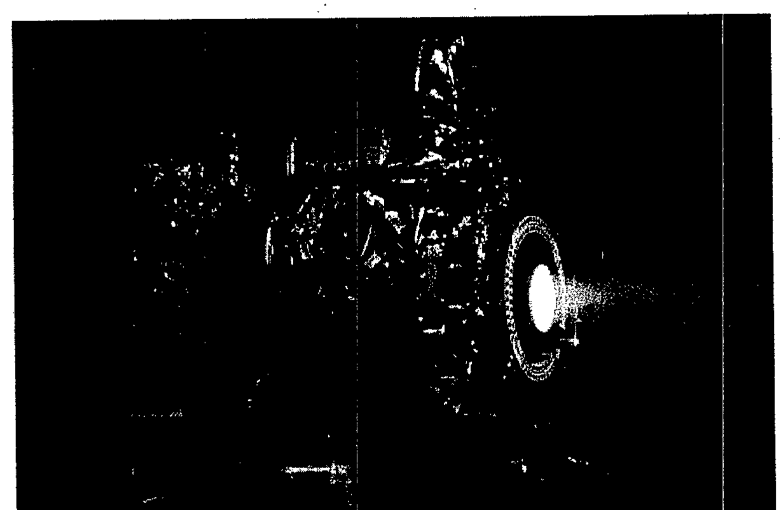




NASA's NSTAR
30cm Ion Engine



Isp = 1500-4000 sec
η = ~65%
Thrust = 1-100 mN



NSTAR Ion Thruster Operating on the DS1 Spacecraft
During the "Thruster Compatibility Test"

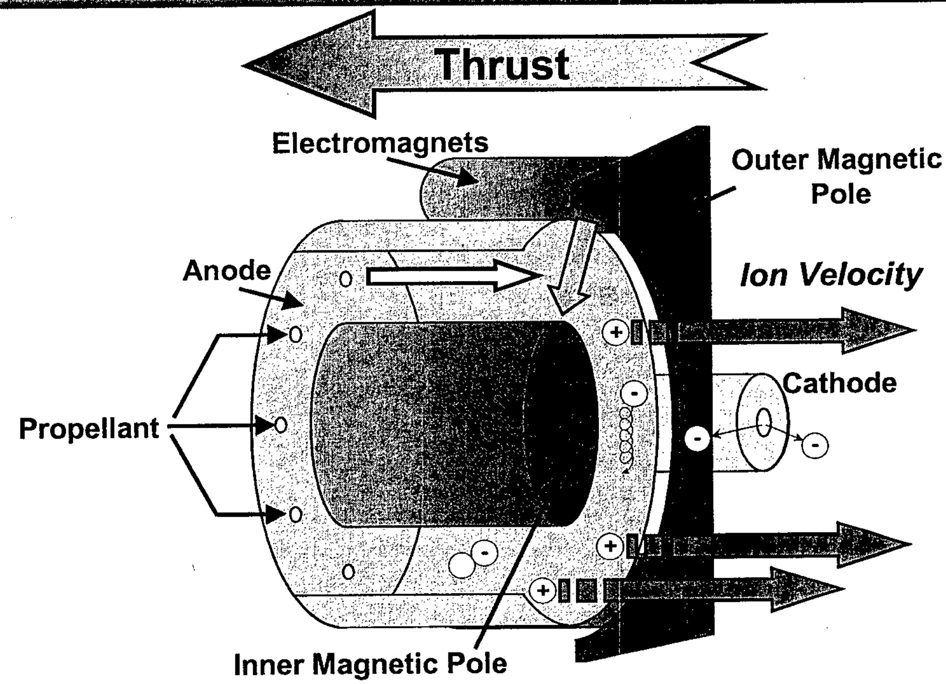
Hall Thruster

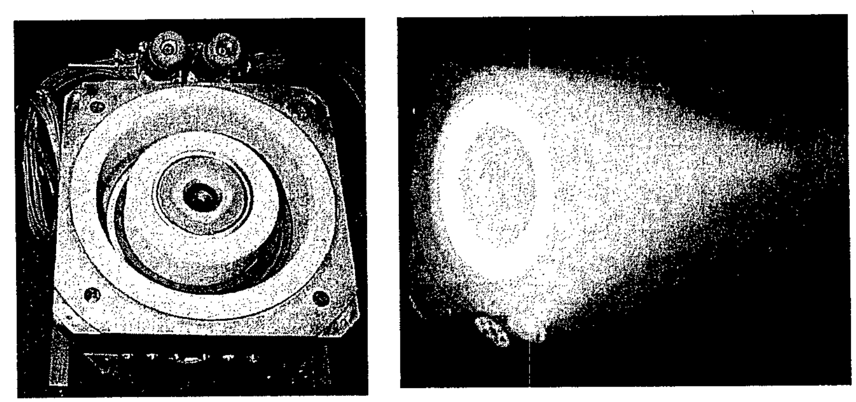
•Principle:
Electromagnetic Acceleration of Ions

•Propellant: Xe, Kr

Isp = 1000-3000 sec
η = 30-60%
Thrust = 5-400 mN
Power = 50W - 4.5 kW

1. Electrons emitted from the cathode travel toward the anode.
2. Electrons are impeded in the discharge channel by a strong radial magnetic field, causing a strong axial electric field to concentrate in this region.
4. This electric field heats the electrons, which subsequently ionize gaseous propellant (xenon) emitted near the anode.
6. The ionized gas accelerates axially through the electric field in the discharge channel, exiting the device at high speed, thus producing thrust.



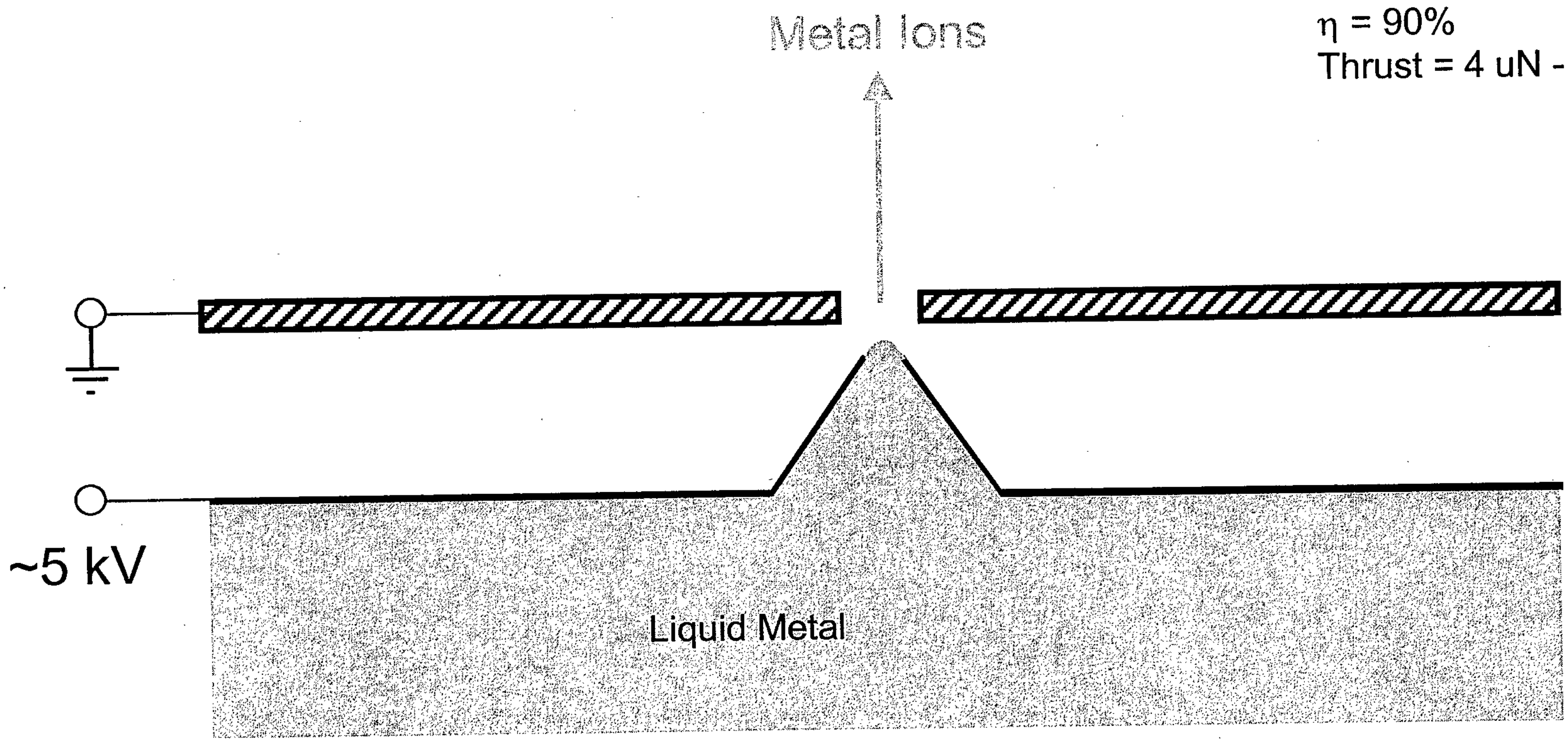


Stationary Plasma Thruster (Fakel, Kaliningrad, Russia)

Field-Emission Thrusters

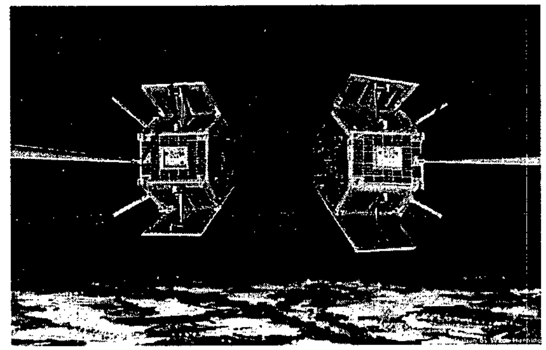
- Principle: Field emission of ions from liquid metal
- Propellant: Cs, Ga, In

Isp = 6000-9000 sec
η = 90%
Thrust = 4 uN - 1 mN

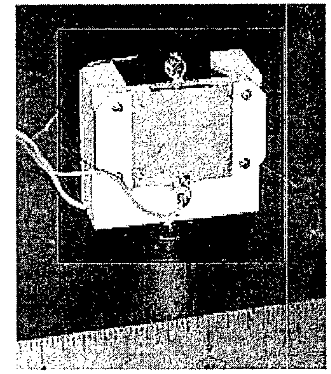


Colloid Thrusters

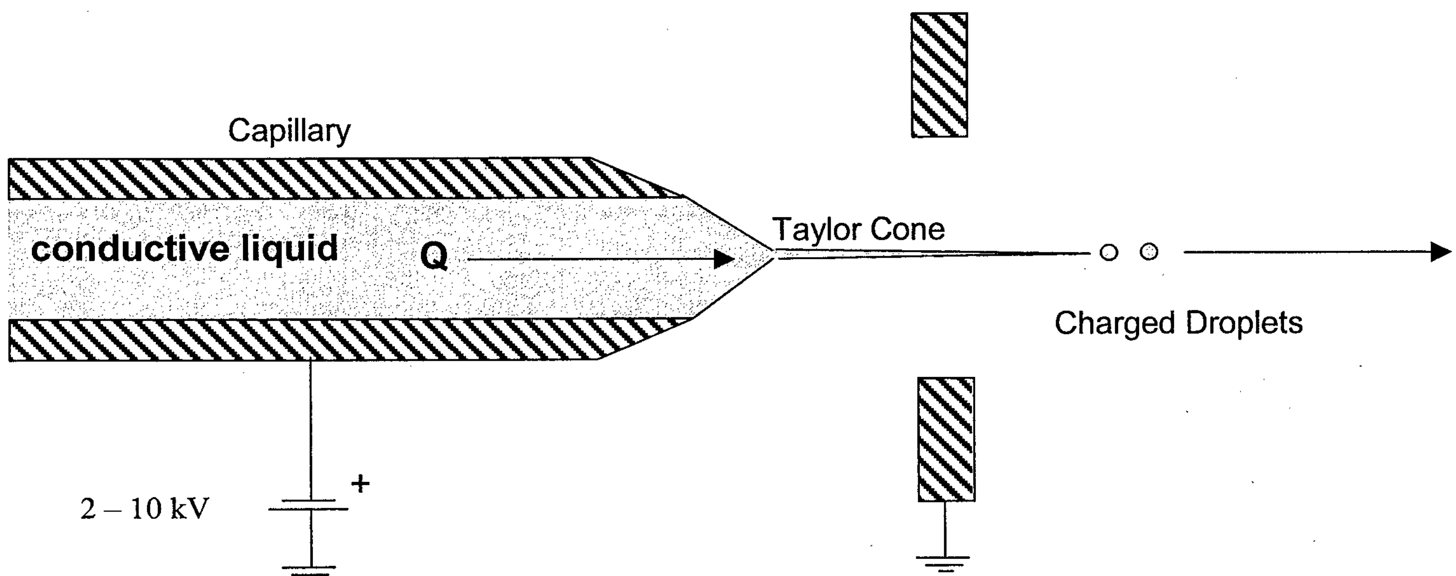
- Principle:
  Electrospray of charged droplets, ions
- Propellant:
  Electrolytes in viscuous,
  low vapor pressure liquids



Stanford EMERALD PAIR
AFOSR/DARPA Support



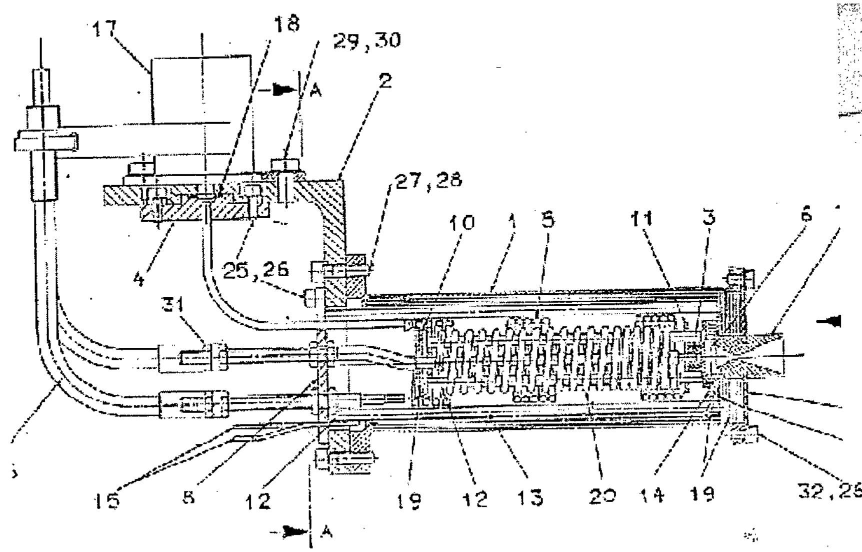
10 cm x 10 cm emitter array

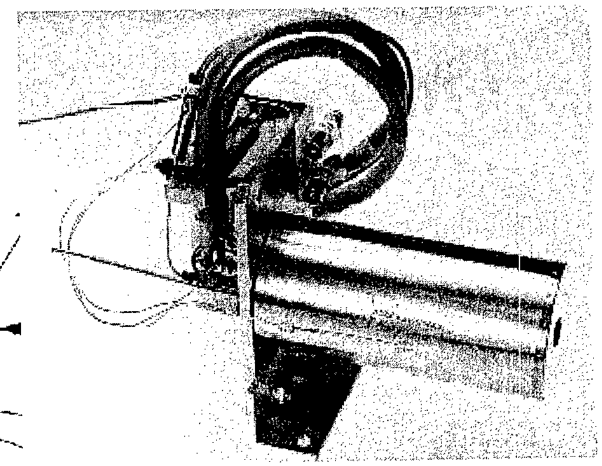


"Other"

Resistojet

Isp = 50-100 sec
η = 10%
Thrust = ~10 mN

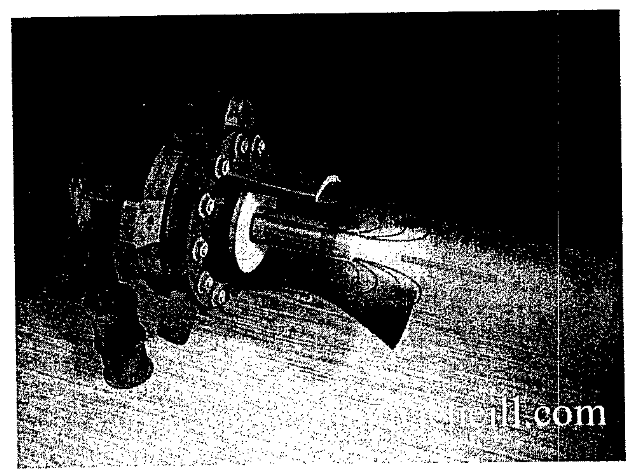


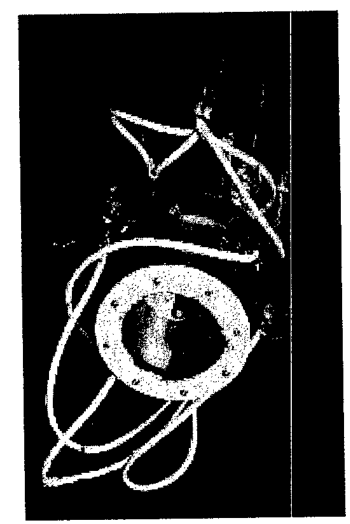


MBB ERNO

Magnetoplasmadynamic (MPD) Thruster

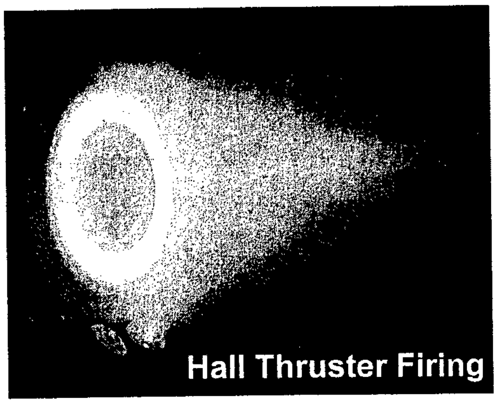
Isp = ~4500 sec
η = 30%
Thrust = ~1 N (Steady)
~10 N (Pulsed)

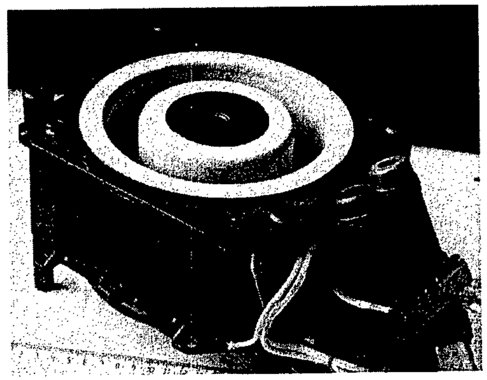




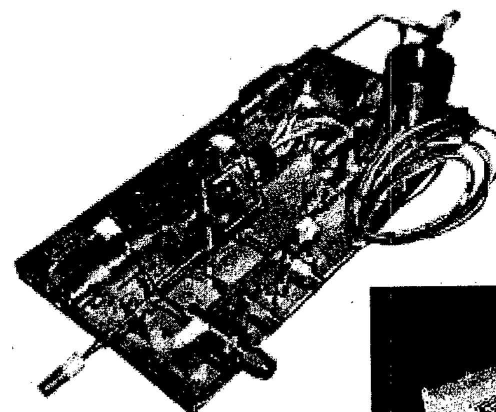
U.S. Government Hall Thruster Programs

Hall Thruster
Technologies Under Development

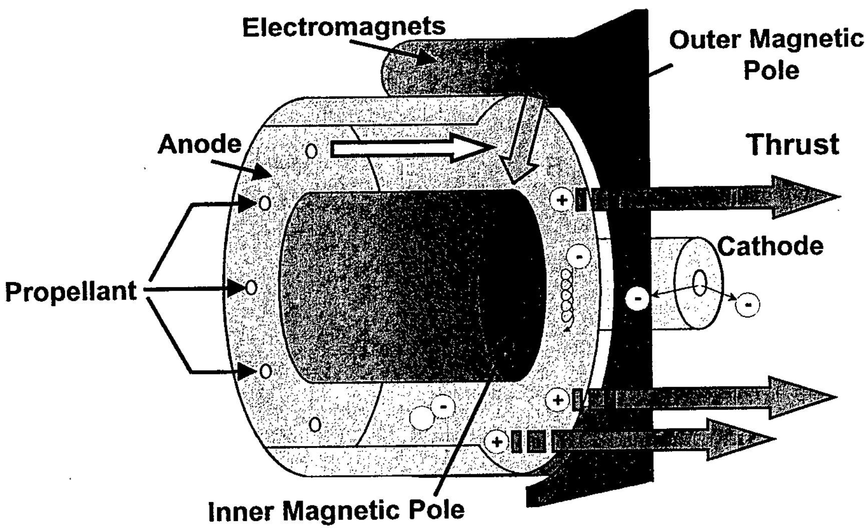


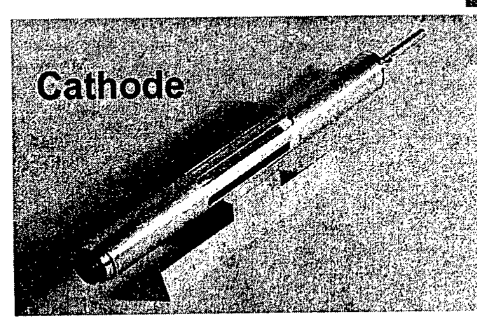


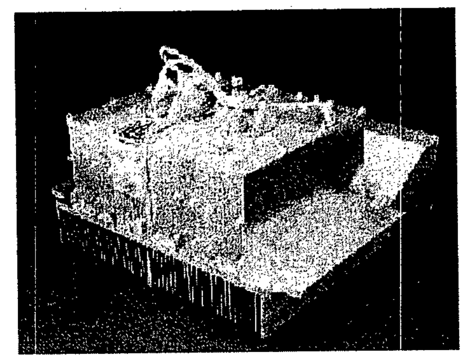
Hall Thruster



Propellant Management Assembly





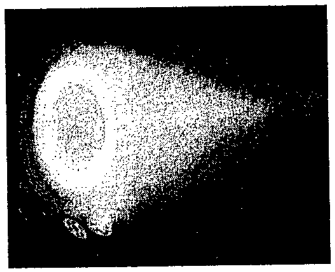


Power Processing Unit

Programs Meeting IHPRPT Goals

USAF – High Performance Hall System

Electrostatic Phase I



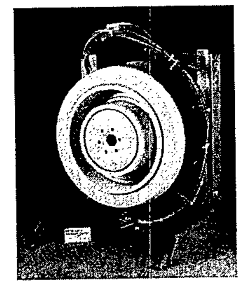
IHPRPT OBJECTIVE STATUS:

	OBJECTIVE	STATUS
I_{sp}	>1800 sec	1856 sec
Efficiency	>51%	55%
Lifetime	>7200 hours	Begin Test Feb01
Specific Mass	<6 kg/kW	5.7 kg/kW

- Exceeding all IHPRPT Phase I Objectives
- 22% increase in I_{tot} / M_{wet}
- Program Completes in December 2002

NASA – 10 kW T-220

Electrostatic Phase II

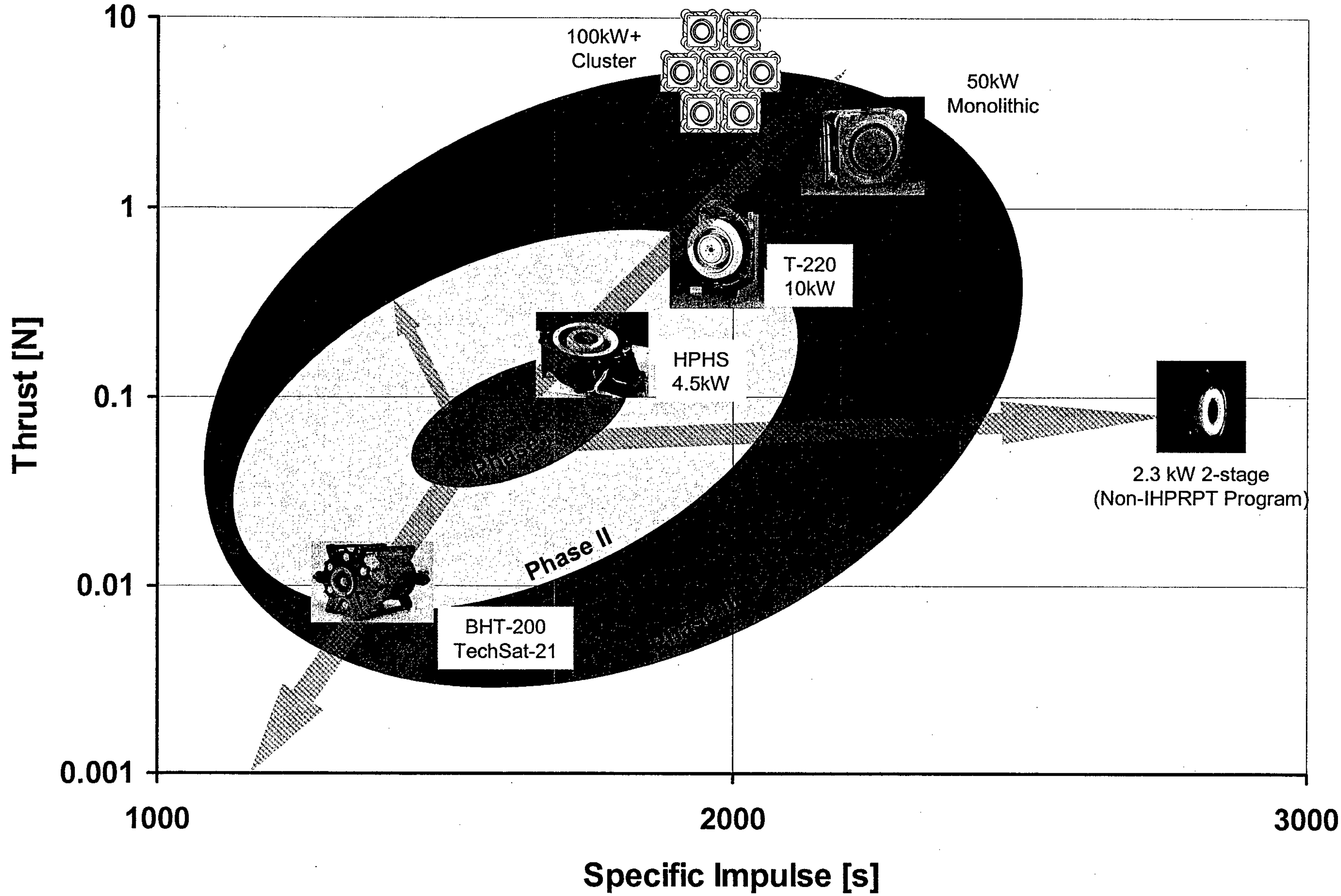


IHPRPT OBJECTIVE STATUS:

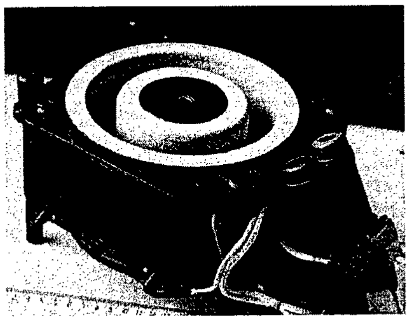
	OBJECTIVE	STATUS
I_{sp}	>2000 sec	2500 sec
Efficiency	>54%	61%
Lifetime	>8000 hours	Low Erosion After 1000 hour test
Specific Mass	<2.7 kg/kW	TBD

- Expected to meet IHPRPT Phase II Goal of 35% increase in I_{tot} / M_{wet}

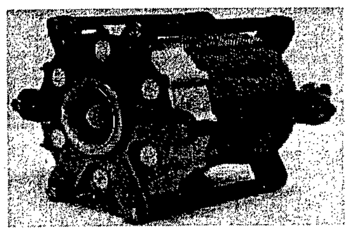
Government Hall Thruster Programs



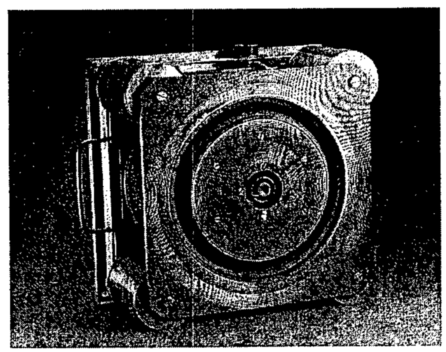
Technology Development Cost



Stationkeeping/Orbit Topping



Small Sat Maneuvering

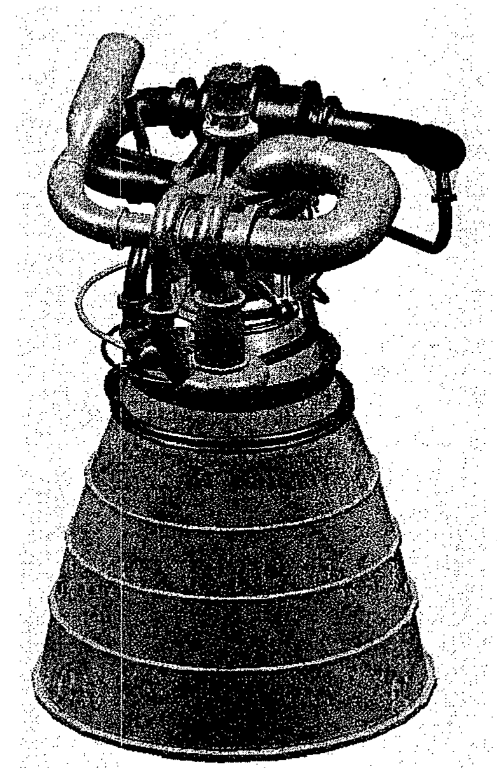


Orbit Transfer

Hall Thrusters for Multiple Missions

$17M

VS



Integrated Powerhead Demo

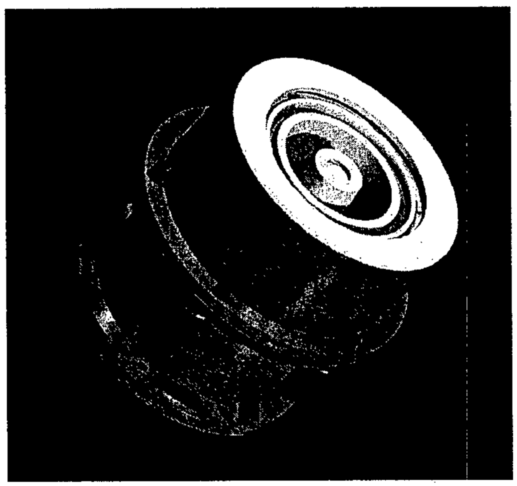
$80M

200W Hall Thrusters

AFOSR/AFRL SBIR Funding

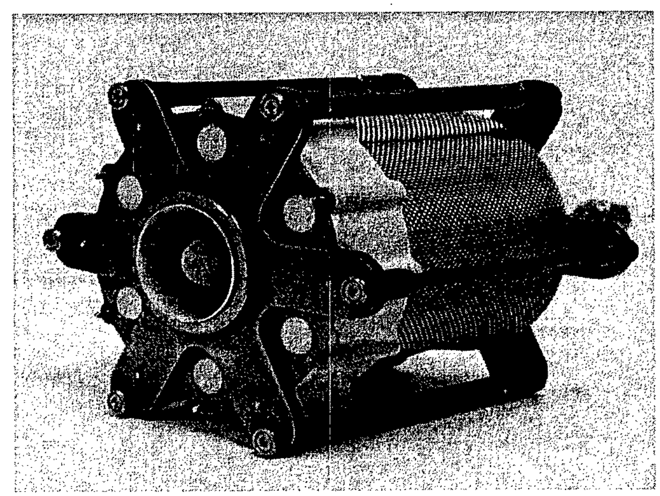
Space Power Inc

- Thruster: AFOSR SBIR
- PPU/PFS: BMDO SBIR
  (Managed by AFRL)



Busek Co.

- Thruster: AFRL SBIR
- PPU: AFOSR STTR

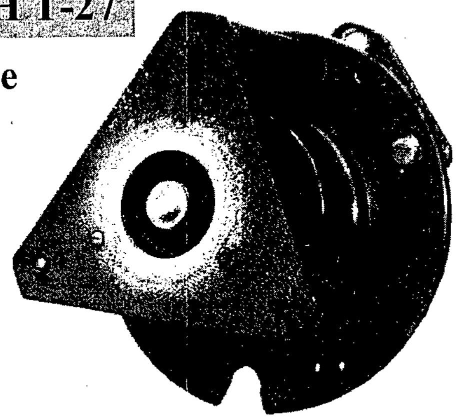


- Both systems tested at AFRL, spring 2000
- Busek 200W Hall selected for USAF TechSat 21 flight demonstration
- Busek 200W delivered to MIT for plume measurements in preparation for MIT Hitchhiker on Shuttle

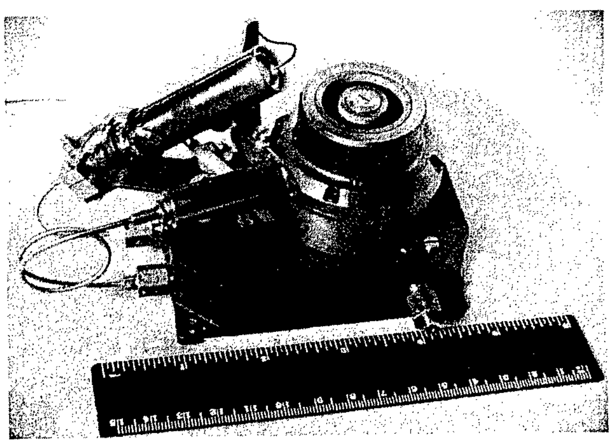
100W Hall Thrusters
Fakel, Tsnimash – EOARD Funding

TSNIIMASH T-27

Characterized performance from 40 – 150W
Measure effects of varied:
- Power
- Propellant flow rate
- B field Strength



FAKEL 100W Hall & Miniature Neutralizer

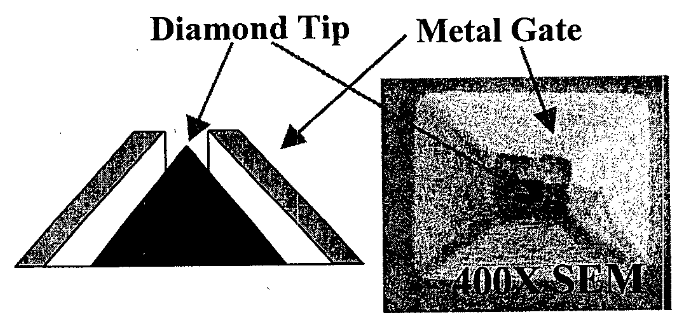


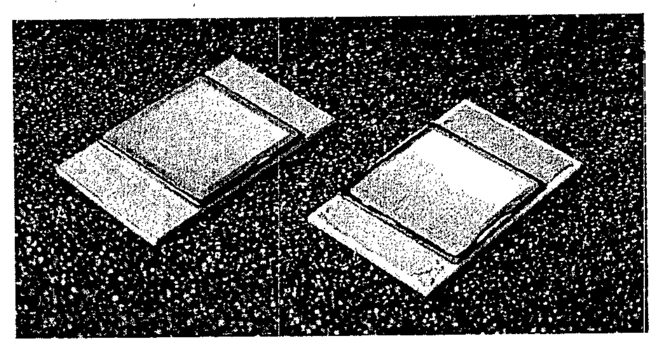
Power = 94.5 W
Thrust = 4.7 mN
Isp = 1000 s
η= 24% (incl. cathode)

Hardware delivered to AFRL

Diamond Field-Emission Cathodes
Busek – AFRL Phase II SBIR

- Low Power , No Propellant
- Characterization in progress





Each 1 cm^2 array has 100,000 Emitters

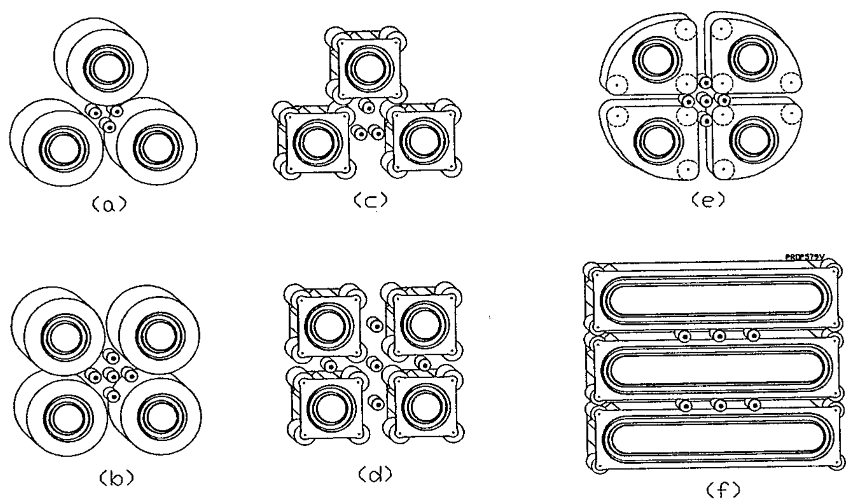
Hall Thruster Cluster R&D

Busek & AFRL - AFRL Core and SBIR funding

BUSEK

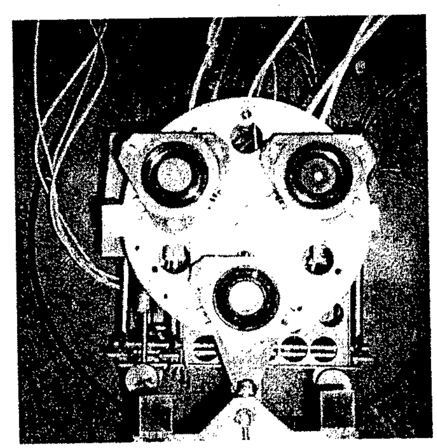
Goal: Investigate cluster issues using small grouping of low-power Halls (~600W)
- Enables cluster testing in smaller chambers

Cluster options for R&D effort:



Research Issues:
- Predict cluster S/C interaction using plume measurement from single thruster
- Determine degree of electrical cross-talk through plume plasma
- Determine optimal geometry
- Investigate neutralization techniques

Primary Goal for FY01:
- Identify critical issues requiring Basic Research
- Fire cluster at AFRL and characterize performance and behavior



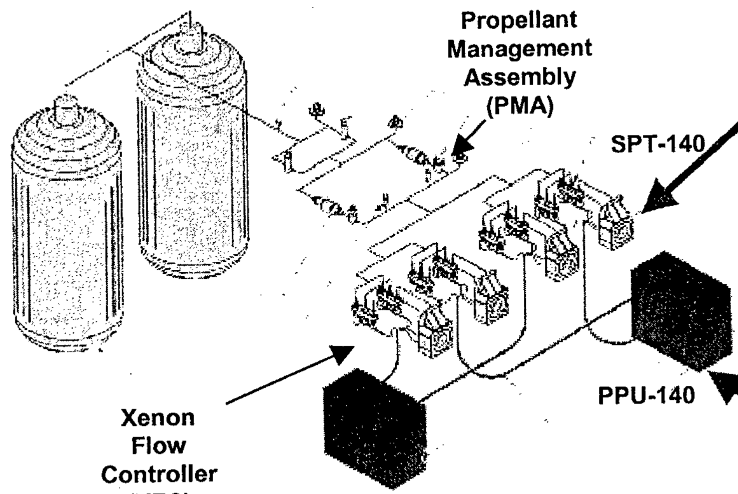
COMPLEMENTARY PROGRAM:

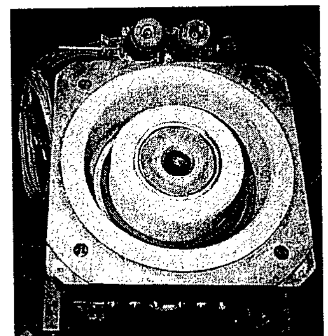
AFOSR/AFRL-Sponsored Hall Cluster Research at TsNIIMASH

Mission and Integration Issues

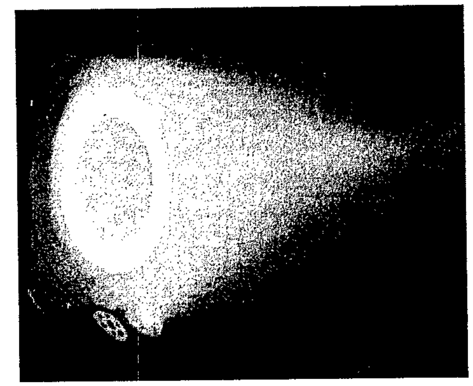
Hall Thruster Integration Hardware

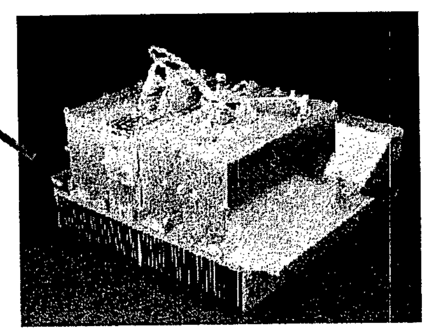
Hall Propulsion System





SPT-140 DM-3





PPU-140 Brassboard

EP Thruster-S/C Interactions

EP Engines Emit High-Energy Particles

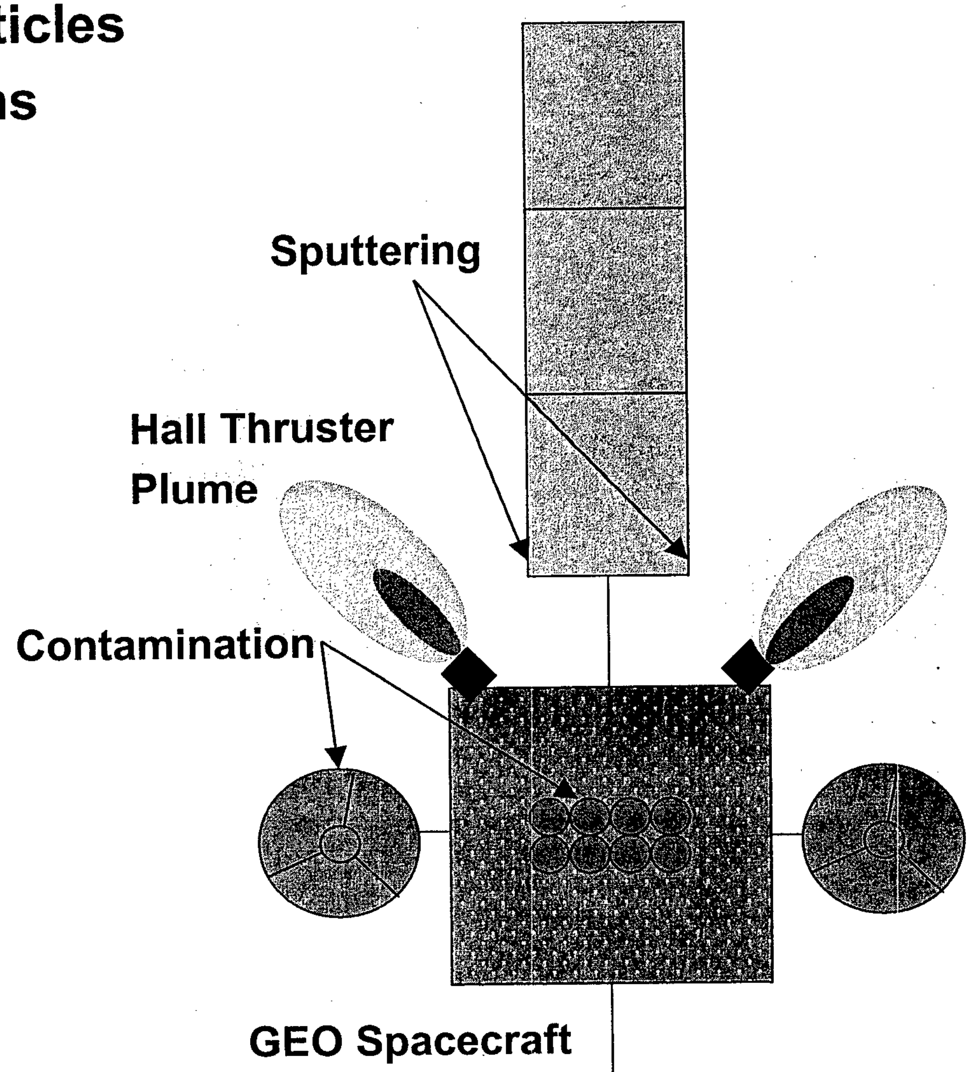
Hall/Ion Engine: ~300eV Xenon Ions

<u>Need to Predict:</u>

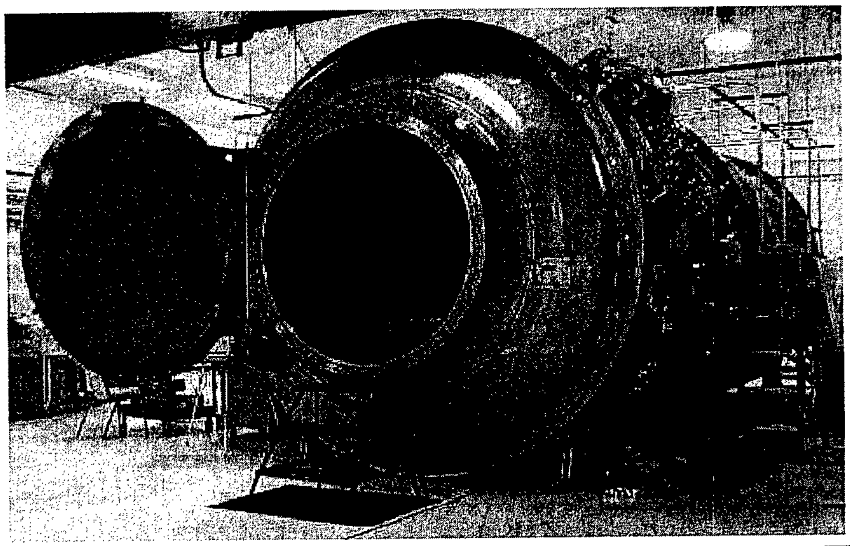
- Contamination and Sputtering of Spacecraft Surfaces
  - Solar Arrays
  - Radiators
  - Sensors
  - Optics
- Cross-Contamination (S/C Clusters)
- Electromagnetic Interference
- Spacecraft Charging
- Observability

<u>Approach:</u>

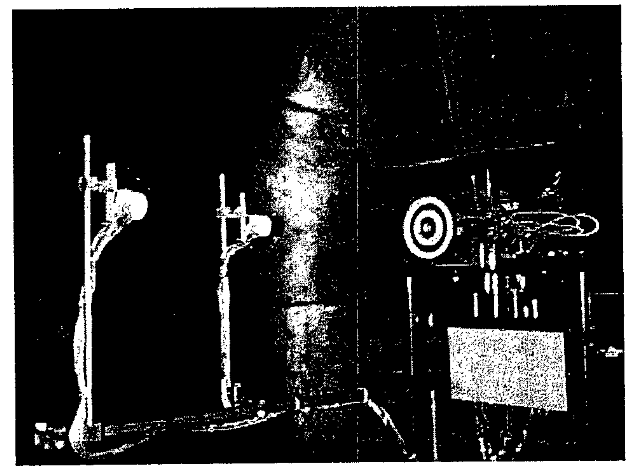
1. Ground and Flight Testing
2. Modeling and Simulation



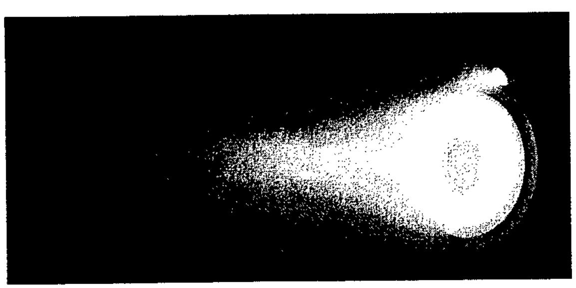
EP Risk Reduction
Testing and Modeling



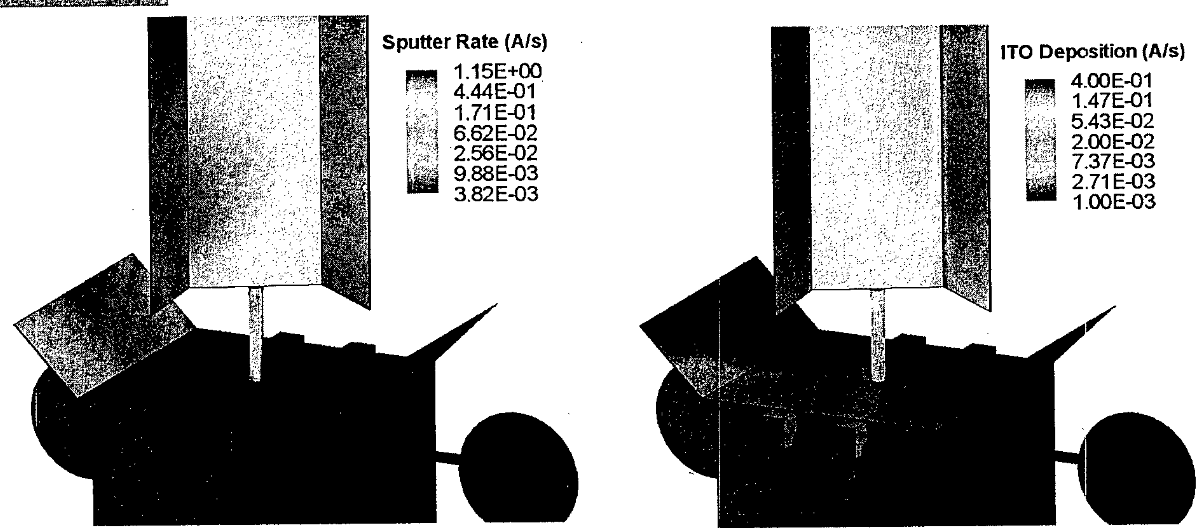
AFRL Hall Thruster Life Test Facility



SPT-140 During Plume Divergence Testing



SPT-140 During Performance Eval



Modeling and Simulation of Thruster-Spacecraft Interaction

Summary

- Electric Propulsion (EP):
  - Decreases spacecraft fuel fraction
  - Increases spacecraft capability
  - Enables new missions
- USAF has selected Hall thrusters for intensive development due to optimum I_{sp} for many AF missions.
- Integration issues are a concern, and the focus of current research